Visual Comput (2007) 23: 843–849
DOI 10.1007/s00371-007-0159-y
ORIGINAL ARTICLE

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Haptic feedback in mixed-reality environment

Published online: 21 June 2007

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Abstract The training process in industries is assisted with computer solutions to reduce costs. Normally, computer systems created to simulate assembly or machine manipulation are implemented with traditional Human-Computer interfaces (keyboard, mouse, etc). But, this usually leads to systems that are far from the real procedures, and thus not efficient in term of training. Two techniques could improve this procedure: mixed-reality and haptic feedback. We propose in this paper to investigate the integration of both of them inside a single framework. We present the hardware used to design our training system. A feasibility study allows one to establish testing protocol. The results of these tests convince us that such system should not try to simulate realistically the interaction between real and virtual objects as if it was only real objects.

Keywords Haptic · Mixed-reality · (Novel) User interfaces

1 Introduction

In the industry, the traditional training of workers to use special equipment is normally carried out using a part or full real equipment. This could be afforded by the industry itself or specialized centers for training. But it brings many drawbacks: the cost of equipment just for training is too high; machines are innovating and training equipment should change; new products or improvements of the production line which implies new training; outsourcing training with specialized centers, etc. Beside this kind of training, there is also more specialized training like aviation or surgery where it is not always possible to use real equipment and to check all the cases that the trainee could face.

Because of this, the help of computer solutions has been considered. They offer lower cost and more adaptability. The simulation of a working environment with computers is done by means of virtual reality (VR). In these applications we are able to build any kind of scenario, tool and equipment. A complete and detailed simulation of some scenarios could be very complex to develop, and moreover it is still difficult to produce truly convincing results.

Thus, to reduce the programming effort and also to simulate better the reality, mixed reality (MR) provides a good solution [11]. This consists of superpositioning real images (pictures or video) inside a virtual world or vice versa. It can provide a complete real scene with virtual elements that help with the training process, as it is shown on the Fig. 1 achieved in the framework of the STAR European project.

These technologies are affordable and good enough to simulate working cases. They can show the proper way to play a role inside a context. Normally, these technologies are limited to keyboard or mouse interaction, in some cases other user interfaces are used, like large screens or touch screens. But this is still far from real, and far from the benefits of the traditional training process with real equipment. Thus, we propose to improve the interaction in such mixed-reality training environments using haptic technologies. in order to provide to the user the possibility to manipulate 3D objects with his both hands.

Fig. 1. A mixed-reality industrial training environment [13]

The benefit of manipulating objects is to teach the user in a practical manner the proper way of performing tasks. For example, in assembly process: the user can manipulate virtual objects and position them. In this paper, we propose a generic assembly training system, which takes advantages of mixed-reality techniques, with haptic feedback. To illustrate our words, we will describe an application of table assembly, with virtual (the feet) and real (the board) parts.

The next section presents an overview of the mixed-reality techniques and applications and observations about the haptic rendering for manipulation tasks. The rest of the article deals with the system that we have created to test the haptic feedback in a mixed-reality environment. First, we will present the hardware used: a haptic device, a tracking system and a head-mounted display. Then, we will present the testing protocol used. And finally, the paper ends by presenting the general recommendations that we have extracted from our experience.

2 Related works

In this section we will present some systems which use haptic interfaces, virtual/mixed reality to simulate assembly or manipulation tasks for training purposes. Concerning mixed-reality, the work of Azuma [1] gives an overview on the recent advances in the field. In his article, haptic user interfaces are discussed as a new approach.

A VTT project [6] is presented a virtual technical trainer for milling machines. The authors use as prototypes three kinds of force feedback devices: the Phantom, a home-made 2DOF haptic device, and a pseudo-haptic technique. They present, in [3], an evaluation of these devices considering the efficiency criteria of the industry. Assembling training has also been addressed for aeronautic purposes in [5]. Authors use a Phantom to simulate mounting/unmounting operation of different parts of an aircraft. These works present virtual environments to simulate machines or scenarios; and use generic or specific haptic interfaces. However, these haptic devices, like the Phantom® [10], only provide force feedback on a particular point, which make them limited because people are not be able to use their hands to interact with the training system.

The use of mixed reality has also been considered in the assembly process. In [15], Zauner et al. propose a virtual assembly instructor based on mixed reality. The user uses a see-through head-mounted display to see overlayed interesting information to help him to assemble furniture. Here, the user interacts with real objects using his hands, but the system is limited to real objects manipulation.

Another example of interaction with real objects which moreover provides haptic feedback is in [7]. The authors use sensors to perceive the real environment, and transmit these sensors information to a 6-DOF haptic display with augmented force feedback. This is a truly "augmented haptic" system because the user is able to feel haptic textures of objects that he could not feel with is real hand (like bumps of a sheet of paper).

An approach of hands interaction with virtual objects is addressed by Walairacht et al. in [14]. They present a manipulation system of virtual objects where 4 fingers of each hand of the user are inside of a string-based haptic device allowing one to feel the virtual objects. Moreover it is a mixed-reality system because the video of the hands is overlaid on the virtual world to provide better visualization of the hand posture. But in this system the user can only manipulate virtual objects.

Recently, in [2], Bianchi et al. have presented a study on the calibration of an augmented reality system that uses a Phantom. The method chosen in our paper to calibrate the system is similar to their method.

In this paper we provide the possibility to interact with real and virtual objects at the same time. The user will be able to use his both hands by the mean of a Haptic Workstation™, which is a generic haptic hardware. We present a sample application that uses virtual and real parts: the assembly process of a mixed-reality table. The next section provides a complete system description of the framework.

3 System architecture

In a training context, haptic and visual, real and virtual, should be brought together within a single application. The feasibility application that we elaborate consists of building a MR table with a scale of 1/4. It is constituted by a 55 cm long and 22 cm large piece of wood that contains also four holes where the feet are driven in. Four virtual objects stored as a 25 cm long cylinder shape represents the feet.

In this section, we present the devices and the software used to create such an application: a haptic system, a tracking system, a see-through head-mounted display (HMD). They are combined as it is illustrated in Fig. 2. The Haptic Workstation™ device is described in the first subsection. Then, we discuss about the tracking system of the real objects. And finally, we present some important facts about the assembly training system.

3.1 Haptic interface

The Haptic Workstation™ is composed by four usual devices of virtual reality. A pair of **CyberGloves** used for acquiring hand posture. They are used to build a mesh representing the hand. This mesh is only used with the collision detection system since in this mixed-reality framework, we do not display the hands. There is also a pair of **CyberGrasp** used to add force feedback on each finger. It is a one-direction force feedback, specially designed for grasping simulation. Concerning the force feedback on the arms, a pair of **CyberForce™** which is an exoskeleton used to convey a 3D-force located on the wrist. This device could not be used to change the orientation of the hand. In our framework we use it to simulate the weight of the grasped objects, the collision with the virtual objects, and to provide a haptic guidance mechanism. Finally, a pair of **CyberTrack™** encapsulated in the CyberForce device to get the position and the orientation of user hands. Refresh rate of this device is very high (nearly 800 Hz) and accurate: they detect a 0.1 mm movement and a change in the orientation of $1/10°$.

In the next subsection, we present the haptic rendering software to manage this haptic workstation.

3.2 Haptic rendering software

The Haptic Workstation™ is a not a usual device: The user interacts mainly with its hands. In comparison with the a Phantom®, where the user interacts using a single point (the fingertip or a pencil), the computation of collision detection and force feedback response is more complex. Existing libraries (Chai3D, OpenHaptics, ReachIn) do not really address this problem (except Virtual Hand, but this last one has other drawbacks: static scene, usability, etc.). Thus we have created a new framework allowing interaction with hands and computation of appropriate force feedback: it is internally called MHAPTIC, by analogy with MVISIO [9], a pedagogic multi-device visual rendering engine developed in our laboratory.

We will not go into an exhaustive description of the library. We can mention that the library runs three concurrent threads as presented on the graphic Fig. 4. It is commonly stated that a correct haptic feedback should be refreshed near 1000 Hz, and the visual feedback near 60 Hz. The physic thread embeds also a collision detection system, and a dynamic engine. This is built using the AGEIA Novodex library.

3.3 See-through head-mounted display

In a mixed-reality system, virtual and real should be visually blended. Usually, two kind of devices are allowed: a video head-mounted display and a see-through head-mounted display (HMD).

Our implementation uses the *Sony Glasstron PLM-S700* see-through HMD. The advantage of such an HMD in comparison with video HMDs is the quality of the real environment display: the reality is not “pixelized”. However, there are also drawbacks: they are usually semi transparent, and a virtual object could not completely occlude the reality. Moreover, the Glasstron HMD has tinted lenses (It could vary from opaque to tinted as standard sunglasses). Thus, the color of the real environment is altered. But it in a bright room, it does not really affect the user experience.

This HMD is calibrated using the SPAAM method [12]. It displays only the virtual feet because they are the only virtual object (see Fig. 5).

3.4 Tracking device

Under mixed-reality conditions, real and virtual have to be well-aligned to avoid confusing the user. Moreover, with a haptic enhanced framework, real and virtual objects must collide with each other, allowing the user to inter-

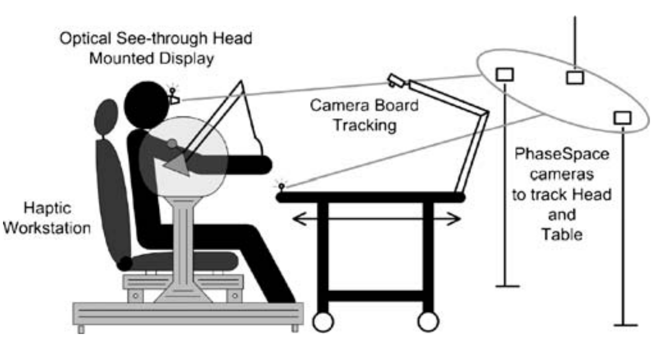

Fig. 2. General scheme of the four hardware modules of our application

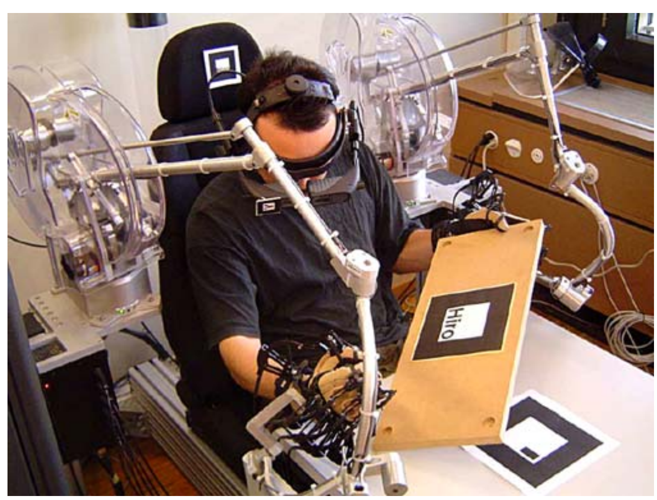

Fig. 3. The immersion haptic workstation

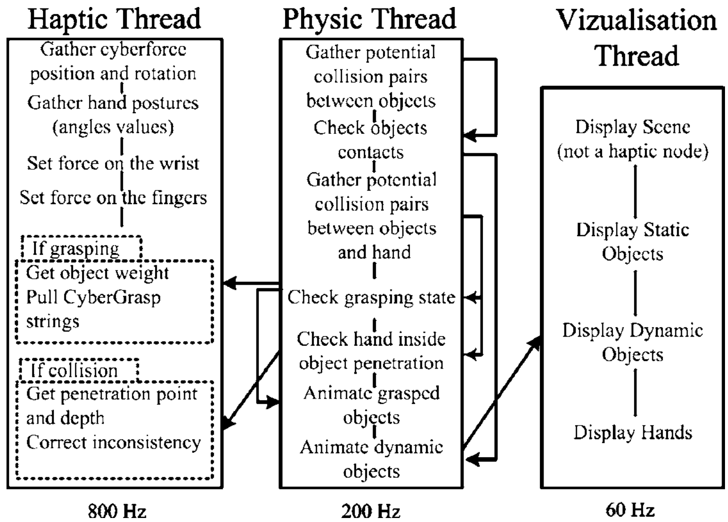

Fig. 4. The three main threads running with MHAPTIC

Fig. 5. Photo taken from the user point of view, and augmented with what is displayed in the HMD

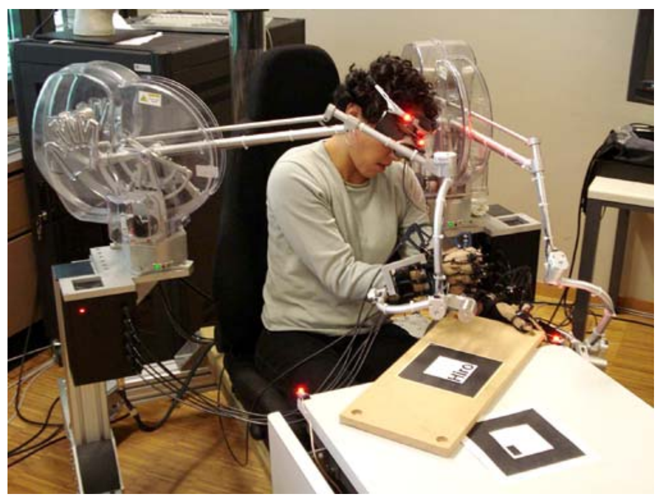

Fig. 6. Photo of the devices used to build our mixed-reality system

act with virtual objects as well as with real objects. This implies that we know the shape and the position of each object of the system in realtime. This is not really a problem for the virtual objects, but, it is of course an unknown for real elements. As we have restricted our system to rigid objects, the shape of real objects could be statically stored. But the position and orientation values are dynamic and have to be estimated for real objects during the simulation. In our feasibility study, three objects have to be tracked: the user's head (the HMD in fact), the board of the mixed-reality table, and the table where all the objects are putted (see photo and schema in Figs. 2 and 6).

We have used two different tracking methods. The first one could be considered as a software solution since it is based on the library ARToolkit, using only a standard webcam. We track the board with this method because it is truly wireless. The second one is a complete hardware dedicated system. This hardware is provided by PhaseSpace Inc., and consists of linear hi-resolution cameras that track LEDs. The LEDs have to be connected to a little box (size of a PDA) that communicates wireless with the main controller. In our case, the workspace is located around the Haptic Workstation$^{\mathrm{TM}}$(it sizes $1.5\,\mathrm{m} \times 1.0\,\mathrm{m} \times 1.0\,\mathrm{m}$). Inside, an estimation of the position of each LED is given with a 1 mm accuracy. Combining at least 3 LEDs on a rigid object allows for extrapolating the orientation. This is the method that we choose to track the HMD and the support for the MR table.

3.5 Assembly training system

The hardware and software that we described in previous sections meet the requirements for creating a mixed-reality application. The real objects can interact with the virtual ones. The user is able to grasp a virtual foot. This is managed by the MHAPTIC library. Then a haptic guidance system tries to move the user's hand in the location of the nearest board hole. This is achieved by applying a force vector to his hand whose direction is equal to the foot extremity/board's hole vector. The norm of the vector diminishes with the distance. When a virtual foot collides with one hole of the table and that foot is perpendicular to the board, the force feedback response simulates the driving-in feeling.

4 Results and evaluation of the system

In this section, we first present the testing protocol, and then we give a general evaluation of the complete system. Finally, we elaborate recommendations, based on our experience, to build an efficient mixed-reality system that includes force feedback.

4.1 Experimentations

The described system integrates complex and heterogeneous VR devices that are not designed to work together. These devices need calibration procedures (we created it for the Haptic Workstation^{TM} [8], and we used SPAAM [12] for the HMD). These calibration procedures could introduce errors, and the sum of these errors could lead to an unusable system. This subsection presents tests that will be useful to evaluate objectively these errors.

When dealing with mixed-reality and haptic applications, it is important to have an efficient mix between real and virtual. This is achieved by two components: the tracking of the real dynamic objects, and the projection of the virtual objects using the HMD. This lead to the first test which consists of measuring the difference between virtual and real environment: we ask to a user to grasp a virtual foot and to try to place it visually inside the hole of the table. Within perfect conditions, the system should detect that a foot is inside a hole and apply the “driving-in” force feedback. However two approximations have been done: first, the board position is evaluated by the tracking system; second, the virtual foot is displayed with the HMD and does not superpose perfectly on the reality. Thus, by measuring the distance between the virtual foot and the board’s hole as they are stored in the system when they should be aligned, we approximate the addition of these two errors. We performed this test many times, moving the head and the board inside the workspace ,and we present the results in Fig. 7.

The second test quantifies how the user is perturbed by this difference: Is he able to assemble the table under these conditions? In normal conditions, the user sees only the real table board and the virtual feet. Thus, we compare the time taken to assemble this mixed-real table and the time taken to assemble a complete virtual table (without see-through). Finally, we have also done a test including the haptic guidance system: when the user grasps a virtual feet, he feels a force guiding his hand to the position where he can assemble the feet to the board. In this last situation, we can also evaluate if the user is perturbed by being guided to a place where visually, he is not supposed to assemble the table. To perform this test, we have asked six persons to try the system. Usually, we ask that the people

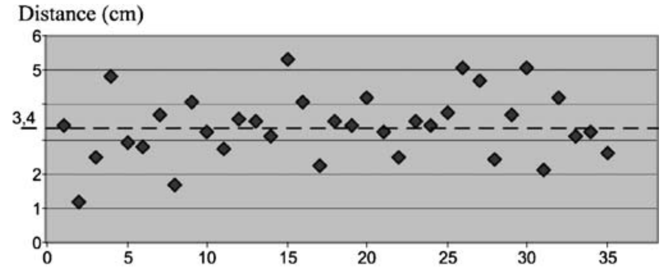

Fig. 7. Distance between real and virtual environments measured by the first test (35 measures)

do not have a particular background in haptics and VR. However, in this case, we consider both the fact that the devices are complex, and that even if this system was applied to the industry the trainee should have a period of accommodation with the devices. Thus, we chose to ask people who are familiar with VR devices (and especially the tracked HMD). Three “challenges” have been created:

1. To build the table in a completely virtual environment. The table’s board is then virtual, and not tracked by ARToolkit.
2. To build the mixed-reality table.
3. To build the mixed-reality table, with the haptic guidance system.

The order is randomly sorted for each tester in order to cancel any kind of accommodation effect when we compute the mean time. We measure the time taken to perform these actions. Moreover, we gather oral feedback of the user after their test. We present the times in the Table 1.

4.2 Evaluation and recommendations

The previous subsection describes the testing protocol of our system. In this part, we extract results from it in order to finally elaborate recommendations when creating applications combining mixed-reality and haptic feedback.

The first test presents an important fact: despite all the calibration procedures, the matching difference between the real and virtual world is still high. The mean is around 3.4 cm, and the standard deviation is high (0.95 cm): this is because errors are sometimes cumulated sometimes canceled. Moreover, with these results, we present only the difference norm: but we remarked that the “difference vectors” are in every direction of the space. Thus, it seems to be difficult to find a correction improving the matching using the hardware that we have. After a more detailed investigation, the main errors in the calibration procedure are located at the display level. Using the optical see-through HMD calibrated with the SPAAM procedure, we find that a displacement of this one on the face of the user during the manipulation is difficult to avoid. In [2], the authors have used a video-through HMD, device that avoids the difficult calibration of the HMD.

Table 1. Times to build the virtual and mixed-reality table by each user

Test	1	2	3
Tester A	1 min 05	4 min 30	1 min 30
Tester B	0 min 55	2 min 00	1 min 25
Tester C	1 min 30	5 min 00 (Max)	1 min 50
Tester D	1 min 00	1 min 30	1 min 30
Tester E	0 min 45	2 min 10	1 min 15
Tester F	1 min 45	5 min 00 (Max)	2 min 10
Mean time	1 min 10	3 min 02	1 min 37
Rank	1	3	2

The second test shows that the assembly procedure is easier when having only virtual objects, and that our mixed-reality system is as not as fast and efficient as an entirely virtual one. However, as mentioned in the introduction, it is sometimes impossible to have a completely virtual environment for many reasons (cost, complexity) and sometimes the goal of a training system is to teach using the real equipment itself. In these conditions, with a simple feasibility study, we have shown that it is difficult to manage haptic assembly with mixed-reality. This is mainly due to the visual sense that is not truly convincing. Hopefully, we have shown that some haptic techniques could help: the haptic feedback guidance, for example is very efficient in these conditions. The testers understand well that the virtual and real visual environment are not perfectly superposed, and that they will better comprehend the mixed-reality world with the help of the haptic guidance. Now, the main question is to evaluate how much the differences between virtual and real and visual and haptic perturbs the learning curve of the trainee. According to the discussions with the testers, we believe that, in the assembly/manipulation context, the important point is the order of the actions/movements. In this case, haptic feedback and guidance is a good tool because it provides the enactive knowledge that the trainee should acquire.

Finally, we remark that these tests provide good indications on the way to build a haptic system under mixed-reality conditions. As it is explained in the previous paragraphs, the perfect visual matching is difficult to reach. Some studies on pseudo-haptic feedback have shown that the visual channel influences the haptic perception [4]. Thus, a realistic haptic feedback is not mandatory since it will be anyway perturbed by the haptic/visual misalignment. However, augmented haptic feedback, like the haptic guidance mechanism, provides a good solution to build an efficient system. This is the main result of this paper.

5 Conclusion

In this paper, we have presented a system that allows training for manipulation and assembly tasks. It is based on a Haptic Workstation^{TM}, device, which lends itself to bimanual assembly because of its dual exoskeleton. Also, we integrate the use of mixed reality environment that allows one to interact with real and virtual objects at the same time. Moreover the Haptic Workstation^{TM}we used had an optical see-through HMD and a powerful tracking system. The assembly task is improved by haptic guidance. We elaborated also a testing protocol that allowed one to advance some recommendations when dealing with mixed-reality and haptic force feedback.

Even with efficient tracking systems, mixed-reality techniques using optical see-through HMD are not precise enough to superpose correctly the virtual on the real world. The problem is that a small misalignment is acceptable when only the visual sense is stimulated. However, when combined with haptic force-feedback, the mixed-reality world will be much more difficult to apprehend, because of kind of ghost effects. The user feels something that he does not see, or the opposite. This is comparable to the mechanism of pseudo-haptic techniques: the visual channel could “create” haptic feedback. Thus, trying to reproduce realistically an assembly situation in a mixed-reality with haptic feedback context will inevitably lead to a system that is difficult to use. But, in opposite, applying augmented haptic feedback to the user will improve the system usability.

Acknowledgement This work has been supported by the Swiss National Science Foundation (FNS), and partially funded by the European Network of Excellence Intuition (NoE Intuition).

References

1. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B.: Recent advances in augmented reality. IEEE Comput. Graph. Appl. **6**, 34–47 (2001)
2. Bianchi, G., Knoerlein, B., Szekely, G., Harders, M.: High precision augmented reality haptics. In: Proceedings of the EuroHaptics Conference (2006)
3. Crison, F., Lécuyer, A., Mellet-D’Huart, D., Burkhardt, J.M., Michel, G., Dautin, J.L.: Virtual technical trainer: Learning how to use milling machines with multi-sensory feedback in virtual reality. In: Proceedings of the IEEE International Conference on Virtual Reality (VR’05) (2005)
4. Lécuyer, A., Burkhardt, J., Biller, J.L., Congedo, M.: A^4: A technique to improve perception of contacts with under-actuated haptic devices in virtual reality. In: Proceedings of WorldHaptic (2005)
5. Lécuyer, A., Kheddar, A., Coquillart, S., Graux, L., Coiffet, P.: A haptic prototype for the simulations of aeronautics mounting/unmounting operations. In: Proceedings of the IEEE International Workshop on Robot-Human Interactive Communication (RO-MAN’01) (2001)
6. Mellet-d’Huart, D., Michela, G., Burkhardt, J.M., Lécuyer, A., Dautin, J.L., Crison, F.: An application to training in the field of metal machining as a result of research-industry collaboration. In:

Proceedings of the Virtual Reality Conference (VRIC) (2004)
7. Nojima, T., Sekiguchi, D., Inami, M., Tachi, S.: The smarttool: a system for augmented reality of haptics. In: Proceedings of the IEEE Virtual Reality Conference, pp. 67–72 (2002)
8. Ott, R., Gutierrez, M., Thalmann, D., Vexo, F.: Improving user comfort in haptic virtual environments trough gravity compensation. In: Proceedings of WorldHaptic, pp. 401–409 (2005)
9. Peternier, A., Thalmann, D., Vexo, F.: Mental vision: a computer graphics teaching platform. In: proceedings of Edutainment (2006)
10. Salisbury, J.K., Srinivasan, M.A.: Phantom-based haptic interaction with virtual objects. IEEE Comput. Graph. Appl. **17**(5), 6–10 (1997)
11. Tamura, H., Yamamoto, H., Katayama, A.: Mixed reality: future dreams seen at the border between real and virtual worlds. IEEE Comput. Graph. Appl. **21**(6), 64–70 (2001)
12. Tuceryan, M., Navab, N.: Single point active alignment method (spaam) for optical see-through hmd calibration for ar. In: Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR'2000), pp. 149–158 (2000)
13. Vacchetti, L., Lepetit, V., Ponder, M., Papagiannakis, G., Thalmann, D., Magnenat-Thalmann, N., Fua, P.: A Stable Real-Time AR Framework for Training and Planning in Industrial Environments, pp. 129–146. Springer (2004)
14. Walairacht, S., Yamada, K., Hasegawa, S., Koike, Y., Sato, M.: 4 + 4 fingers manipulating virtual objects in mixed-reality environment. Presence: Teleoperators and Virtual Environments **11**(2), 134–143 (2002)
15. Zauner, J., Haller, M., Brandl, A., Hartman, W.: Authoring of a mixed reality assembly instructor for hierarchical structures. In: Proceedings of the Second IEEE and ACM International Symposium on Mixed and Augmented Reality, pp. 237–246 (2003)

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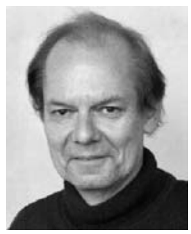

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